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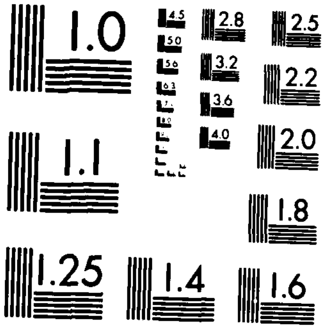

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Fourth Annual Report

DYNAMIC FRACTURE BEHAVIOR OF STRUCTURAL MATERIALS

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To ensure safe design of Air Force structures, it is necessary to understand the mechanics of high-rate fracture and to have a knowledge of the dynamic fracture properties of component materials. In accord with this need, a research program is being conducted at SRI with the goals of developing a test procedure for obtaining reliable dynamic initiation toughness values and establishing the relationship between dynamic initiation and dynamic propagation toughness. This annual report summarizes the progress and results of the fourth research year.

The capabilities of the one-point-bend impact test (1PBT) conceived by Kalthoff et al.[1] and further developed during previous years of this program were extended in two ways during this fourth research year. By adding ballast plates to the ends of a specimen plate we showed that the 1PBT could be applied to lower density materials and smaller specimens than heretofore possible. Second, we developed a model of the post-instability behavior of

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the impacted specimen that allows the test to be used to assess crack propagation as well as crack initiation behavior.

To compare dynamic initiation and propagation toughness, we performed a series of one-point-bend experiments in which K_{Id} and K_{ID} were measured on the same specimen. The propagation toughness values were dependent on crack velocity and propagation distance, and were much larger than the initiation toughness. The year 5 research effort will aim to explain these results, obtain an understanding of how K_{Id} is related to K_{ID}, demonstrate the role of loading-time-to-fracture on dynamic crack instability, and obtaining crack instability data under dynamic mixed-mode loading conditions.

I SUMMARY

To ensure safe design of Air Force structures, it is necessary to understand the mechanics of high-rate fracture and to have a knowledge of the dynamic fracture properties of component materials. In accord with this need, a research program is being conducted at SRI with the goals of developing a test procedure for obtaining reliable dynamic initiation toughness values and establishing the relationship between dynamic initiation and dynamic propagation toughness. This annual report summarizes the progress and results of the fourth research year.

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II INTRODUCTION

Structures used by the U.S. Air Force must be designed to resist catastrophic fracture when subjected to dynamic loads. For example, aircraft components may experience short stress pulses from airborne debris, military projectiles, or intense bursts of laser or x-ray radiation. Landing gear and aircraft retaining cables on carrier ships experience dynamic loads at the end of each flight.

A related dynamic fracture problem concerns rapidly running cracks. For example, it is often desirable to know whether a crack, once initiated, will arrest before it reaches a component boundary and thereby preserve the integrity of the structure. Thus, to ensure safe design of Air Force structures, it is necessary to have a knowledge of the dynamic fracture behavior of the component materials. The research being conducted in this program is aimed at improving our understanding of dynamic fracture. Emphasis is on the accurate characterization of material resistance to crack initiation under dynamic loading (K_{Id} measurements) and to rapid crack propagation (K_{ID} measurements). This annual report reviews the specific program objectives and summarizes the progress during the fourth research year.

III OBJECTIVES

To obtain more accurate measures of dynamic fracture initiation and propagation toughnesses and to establish the relationship between them, we proposed to accomplish the following research tasks in a five-year program:

Task 1 - Based on the new understanding of the role of load duration in crack instability behavior, develop a simple test procedure to obtain reliable fracture toughness values at strain rates representative of impact loading.

Task 2- Generate the necessary data to develop a reliable theory for dynamic crack instability. In particular, measure the minimum time for instability for different K-histories.

Task 3 - Obtain values of the propagation toughness, K_{ID}, by means of heat of fracture, strain gage, or optical strain measurements, and establish the relationship between K_{ID} and the dynamic fracture toughness associated with high loading rate initiation, K_{Id}.

Task 4 - Measure critical conditions and establish criteria for crack instability under mixed-mode, short-pulse loads.

This year our work has focused primarily on the measurement of the propagation toughness, K_{ID}. Additional work in support of Tasks 1 and 2 has also been performed. The progress to date is described in the next section.

IV PROGRESS

The work performed in the fourth year of the program builds upon or extends the results of the first three years. Therefore, we first briefly summarize these previous accomplishments before describing the research effort of the fourth year.

Review of Significant Results of the First Three Years

During the first three years of the program, a new dynamic fracture test, the so-called one-point-bend test (1PBT) was investigated and analyzed.[1] The 1PBT uses a single-edge-cracked specimen and the same testing arrangement as a conventional three-point-bend impact test, except that the end supports are removed. The loading of the crack tip occurs strictly by inertia. The resulting stress intensity histories do not show the undesirable oscillations that often characterize the three-point-bend impact test, but rather have a smoothly varying sinusoidal shape. The maximum stress intensity amplitude and the duration of loading are readily adjusted by changing the impact velocity and the specimen geometry, respectively.

Because of the simple shape of the stress intensity history produced by the 1PBT, this test is attractive for investigating crack initiation conditions under dynamic loading. The controllable inertial loading also makes the test attractive for the study of crack extension because it allows adjustment of the crack extension distance.

We used the 1PBT to investigate crack instability conditions for short loading times--varying from 150 μs to as short as 2 μs--in aircraft quality 4340 steel (HRC 50).[2] The results of these experiments show that for loading times in excess of 25 μs, crack initiation can be determined by using classical concepts of fracture mechanics; a time- modified fracture criterion to account for a microdamage incubation time[3] is not necessary. It was also shown that the dynamic initiation toughness of 4340 steel is not very sensitive to loading rate and only about 8% lower than the static toughness.

During the second research year we performed dynamic crack propagation tests in aircraft quality 4340 steel (HRC 50) using transversely wedge-loaded compact tension specimens. The crack velocity was measured with strain gages evenly spaced along the crack path; the dynamic propagation toughness was obtained by measuring with thermocouples the temperature history near the tip of the fast-running crack.

These measurements yielded dynamic propagation toughness values of 120 to 160 MPa $m^{1/2}$, or about twice the initiation toughness. Further, these values were also much larger than values reported in the literature for similar crack velocities (400 to 600 m/s).

During the fourth research year, the versatility of the 1PBT was improved, and a model of the 1PBT was further developed. The model was used to investigate the relationship between dynamic initiation toughness, K_{Id}, and propagation toughness, K_{ID}, by varying the amount of crack extension and the crack velocity.

Further Investigation of the 1PBT

We have experimentally demonstrated that the addition of ballast plates clamped at both ends of the specimen can considerably increase the maximum stress intensity amplitude achievable with the 1PBT for given specimen dimensions.[4] This is of particular importance when testing materials of lower density and elastic modulus than steel, such as aluminum or titanium. We have also measured the stress intensity history for the standard ASTM bend specimen for several crack depth to specimen width ratios. These results for the most widely used bend specimen geometry complement the data obtained during the third year.

In interpreting the crack initiation data obtained with the 1PBT, we suspected that the formation of small shear lips may affect the near crack tip strain records measured during the test and from which the stress intensity history is calculated. To clarify this point, we have performed dynamic initiation tests with a set of side-grooved and non-side grooved specimens. The introduction of side grooves suppresses the formation of shear lips. These tests demonstrated that the formation of shear lips does not affect the dynamic initiation toughness value measured in the 1PBT. In contrast, the strain history measured after crack initiation in the side-grooved specimens differs significantly from the history measured in non-side-grooved specimens, suggesting that the formation of shear lips may significantly affect crack extension. This point will be further discussed in the next section.

1 PBT Model

During the fourth research year the model of the 1PBT developed earlier in the program was improved to allow approximate estimates of the applied stress intensity or the crack velocity during crack extension experiments. The improved model is based on the stress intensity history measurements for specimens with stationary cracks of various lengths. It assumes that the 1PBT is displacement controlled, with the first flexural mode of the specimen controlling the stress intensity at the crack tip. The model accounts for the effect of crack extension and for the effect of material inertia on the stress intensity at the crack tip. It is implemented on a microcomputer and calculates the stress intensity at regular small time intervals. During each time increment, the crack velocity is calculated using the current stress intensity and the current toughness value according to a procedure proposed by Homma et al.[5] The current toughness is an adjustable variable of the model. The model was used to evaluate the crack extension experiments performed with the 1PBT.

Crack Extension Experiments

To investigate the relationship between dynamic crack initiation toughness and propagation toughness, we performed two types of crack extension experiments in 4340 steel HRC 50. In the first type of experiment, the crack was allowed to run for only a short distance and then it was arrested; the crack velocities were small (≈ 100 m/s) . In the second type of experiment, the crack was overloaded to achieve complete fracture.

For the experiments of the first type, fatigue-precracked specimens were tested in 1PB, each at different impact velocities. Therefore, each specimen was subjected to a nominal stress intensity history--i.e., the stress intensity history that would have resulted, had no crack extension occurred--of constant duration but increasing amplitude. Under this pulse loading, the crack extended a small distance and then arrested. The specimens were then fatigued to mark the arrested crack front position and broken open. The amount of crack extension was measured on the fracture surface. The results of these tests are shown in Figure 1, where the crack jump distance is plotted as a function of maximum nominal applied stress intensity, K_{Imax}^{appl} . Also shown in the figure are estimates of the crack jump distance obtained with the 1PBT model, assuming a constant propagation toughness equal to the initiation toughness. The simulation termed Stiff Model represents a simulation with a lower bound estimate of the stress intensity at the running crack tip. It is seen that the measured crack jump distance increases with increasing K_{Imax}^{appl} but much less than anticipated from the model simulation. This suggests that the resistance to dynamic crack extension increases with crack extension in a manner analogous to that observed in thin sheets or in ductile materials.

In the second type of experiment we performed a 1PB test with a specimen instrumented with strain gages along the crack path. The strain gages served to measure the crack velocity as well as the stress intensity at the running crack tip. The impact was such that the crack propagated all the way through the specimen. The crack accelerated slowly over the first 5 mm of extension and reached a velocity of 400 to 500 m/s. The dynamic propagation toughness calculated from the strain measurements was about 140 MPa $m^{1/2}$ for the range of velocities covered. This value is in the range of the values measured earlier in the program with thermocouples. The complete set of crack propagation data obtained during the program is summarized in Figure 2, which plots the propagation toughness K_{ID} as a function of velocity.

We have also begun to investigate the feasibility of applying the stereoimaging technique[6] to measure the strain field and, indirectly, the stress intensity factor at the tip of a fast running crack. Successful adaptation of this technique would provide a new experimental tool applicable not only to the elasto-dynamic field, but also to the elastic-plastic dynamic field. This year, we performed a crack propagation experiment, using a compact tension specimen loaded transversely by a wedge. A fine grid was etched on the polished surface of the specimen and the extension of the crack was photographed with a high-speed camera. The results of this test are still being analyzed and will be discussed in the final report. Preliminary evaluation of the data indicates that the propagation toughness is very high (170 MPa $m^{1/2}$) although the average crack velocity was only about 270 m/s.

Discussion

The propagation toughness values reported here of 120-160 MPa $m^{1/2}$ for a crack velocity of 400 to 600 m/s are much higher than most values reported in the literature for nominally the same material. However, the values are in accord with the results of Kanninen and co-workers,[7,8] who reported that in order to simulate correctly the crack extension in an impacted three-point-bend specimen of 4340 steel, it was necessary to assume a propagation toughness of 170 MPa $m^{1/2}$. This value is more than two and a half times greater than the initiation toughness or than the propagation toughness measured in conventional crack propagation tests under quasi-static loading. Kanninen et al. have no explanation for this apparent discrepancy.

In our experiments we obtain high propagation toughness values for crack initiation under quasi-static as well as under dynamic initiation conditions. The formation of small shear lips and crack tunneling in all the experiments we performed may be the cause of the high measured propagation toughness. There also may be effects of specimen size, specimen geometry, and the method of initiating the crack.

We will address these questions in the remainder of the program.

Future Work

We expect to complete this research program in the next year. We plan to explain the differences between K_{Id} and K_{ID} measured this year and to establish the relationship between these quantities by performing wedge-loaded compact tension tests and 1PBT's on specimens with and without side grooves. These tests will be instrumented with strain gages and high speed photography.

We will conclude our investigations of the effect of loading-time-to-fracture on the conditions for crack instability by performing a series of 1PB experiments on statically preloaded specimens. Data on crack instability under mixed-mode, short-pulse loads will be obtained by performing 1PB experiments on specimens in which the fatigued-sharpened notch is oriented at a non-90 degree angle to the specimen edge.

V PUBLICATIONS AND PRESENTATIONS

Papers prepared or published and presentations made during the previous program and under the current contract are listed below.

Publications

J. F. Kalthoff and D. A. Shockey, "Instability of Cracks Under Impulse Loads," J. Appl. Phys. 48 (3), 984-993 (March 1977)

D. A. Shockey, J. F. Kalthoff, H. Homma, and D. C. Erlich, "Criterion for Crack Instability Under Short Pulse Loads," Advances in Fracture Research, D. Francois et al., Eds. (Oxford and Pergamon Press, New York, 1980), pp. 415-423.

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D. A. Shockey, J. F. Kalthoff, W. Klemm, and S. Winkler, "Simultaneous Measurements of Stress Intensity and Toughness for Fast Running Cracks in Steel," Exp. Mech. 23, 140-145 (1983).

H. Homma, D. A. Shockey, and Y. Murayama, "Response of Cracks in Structural Materials to Short Pulse Loads," J. Mech. Phys. Solids 31, 261-279 (1983)

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J. H. Giovanola, "Investigation and Application of the One-Point-Bend Impact Test," to appear in the Proceedings of the ASTM Seventeenth National Symposium on Fracture Mechanics, August 7-9, 1984, Albany, NY.

J. H. Giovanola, "The One-Point-Bend Test," contribution to ASM Metals Handbook, Volume 8, 9th Edition on Mechanical Testing (in press).

D. A. Shockey, "Short-Pulse-Duration Tests," contribution to ASM Metals Handbook, Volume 8, 9th Edition on Mechanical Testing (in press).

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J. H. Giovanola, "Crack Initiation and Extension in Steel for Short Loading Times," to appear in the Proceedings of DYMAT International Conference on Mechanical and Physical Behavior of Materials under Dynamic Loading, Paris, September 2-5 (1985).

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D. C. Erlich and D. A. Shockey, "Instability Conditions for Cracks Under Short-Duration Pulse Loads," Topical Conference on Shock Waves in Condensed Matter, Meeting of the American Physical Society, Washington State University, Pullman, WA, June 11-13, 1979.

D. A. Shockey, "Instability Conditions for Cracks Loaded by Short Stress Pulses," Poulter Laboratory Seminar, SRI International, Menlo Park, CA, December 12, 1979.

D. A. Shockey, "Dynamic Crack Instability," Institut CERAC, Ecublens, Switzerland, May 19, 1980.

D. A. Shockey, "Dynamic Crack Instability," Institut fur Werkstoffmechanik, Freiburg, Germany, May 21, 1980.

D. A. Shockey, "Simultaneous Measurements of Stress Intensity and Toughness for Fast Running Cracks in Steel," Poulter Laboratory Seminar, SRI International, Menlo Park, CA (June 1980).

D. A. Shockey, "Criterion for Crack Instability Under Short Pulse Loads," Fifth International Conference on Fracture (ICF5), Canne, France, March 29-April 3, 1981.

D. A. Shockey, "Simultaneous Measurements of Stress Intensity and Toughness for Fast Running Cracks in Steel," 18th Annual Meeting of the Society for Engineering Science, Inc., Brown University, Providence, RI, September 2-4, 1981.

D. A. Shockey, "Short Pulse Fracture Mechanics," Seminar for the Department of Applied Mechanics, Stanford University, Stanford, CA, March 3, 1983, C. Steele, Chairman.

D. A. Shockey, "Short Pulse Fracture Mechanics," Poulter Laboratory Seminar, SRI International, Menlo Park, CA, April 11, 1983.

J. H. Giovanola, "Mechanics of Fracture Under Pulse Loads; Minimum Time Theory Revisited," Poulter Laboratory Seminar, SRI International, Menlo Park, CA, (April 1984).

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J. H. Giovanola, "Crack Initiation and Extension in Steel for Short Loading Times," to be presented at DYMAT International Conference on Mechanical and Physical Behavior of Materials under Dynamic Loading, Paris, September 2-5 (1985).

List of Personnel

Dr. D. A. Shockey, Principal Investigator
Dr. J. H. Giovanola, Project Leader
Dr. T. Kobayashi
Mr. A. Werner

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1. J. H. Giovanola, "Investigation and Application of the One-Point-Bend Impact Test," to appear in the Proceedings of the ASTM Seventeenth National Symposium on Fracture Mechanics, August 7-9, 1984, Albany, NY.

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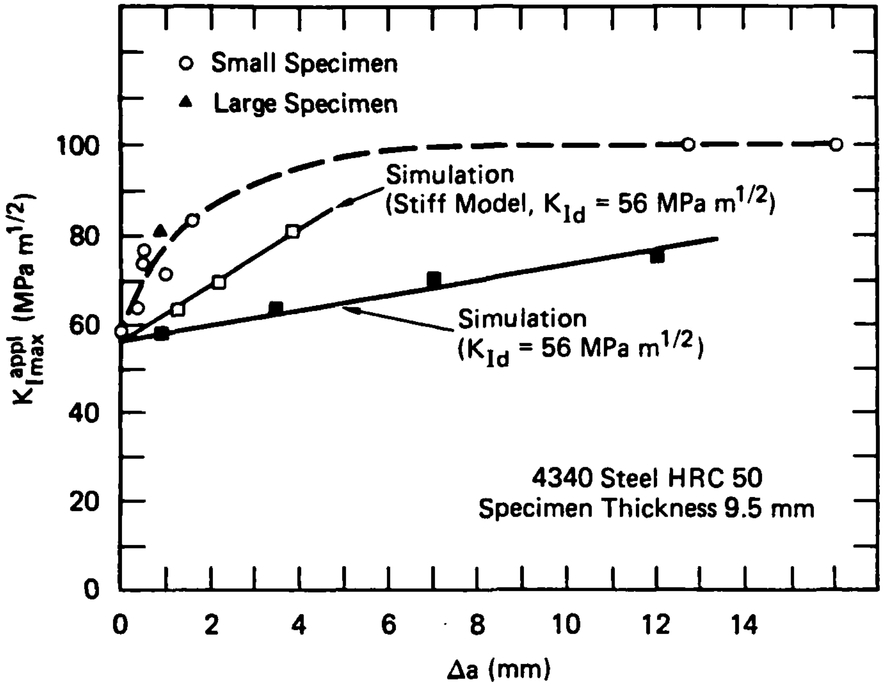

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FIGURE 1 CRACK JUMP DISTANCE Δa AS A FUNCTION OF MAXIMUM NOMINAL APPLIED STRESS INTENSITY FACTOR $K_{I\max}^{appl}$

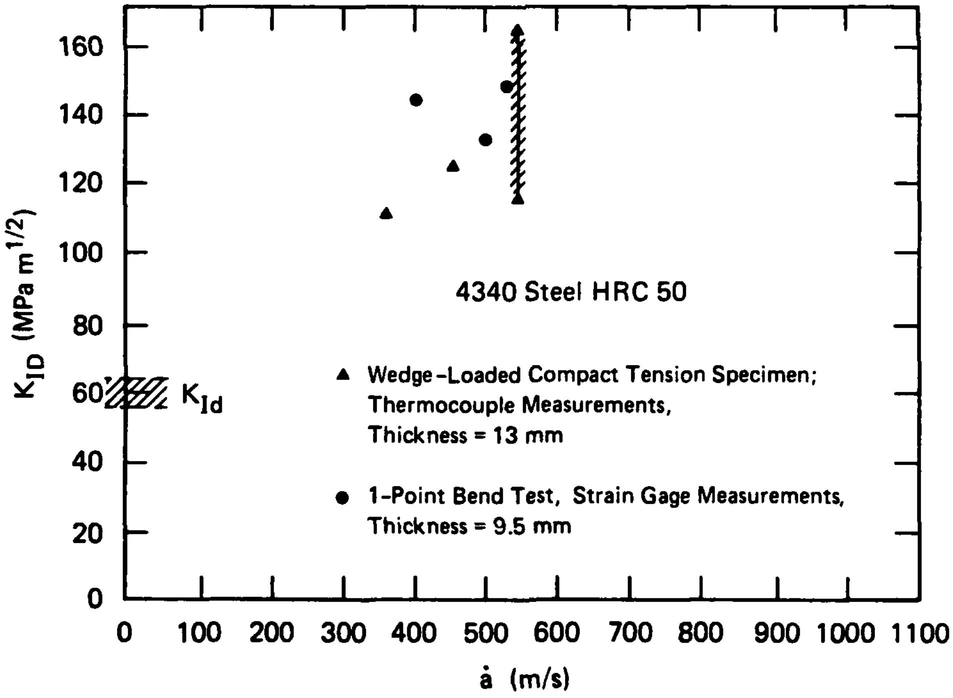

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FIGURE 2 SUMMARY OF CRACK PROPAGATION TOUGHNESS K_{ID} RESULTS AND COMPARISON WITH INITIATION TOUGHNESS K_{Id}